SOIL WATER DISTRIBUTION AND NITRATE LEACHING OF DRIP IRRIGATION CONTROLLED BY SOIL MOISTURE SENSORS

Lincoln Zotarelli[1], Michael D. Dukes[1] y Rafael Muñoz-Carpena[1]*

1: Agricultural and Biological Engineering Department
University of Florida
Frazier Rogers Hall, Gainesville, FL, 32611 USA
P.O. Box 110570,
e-mail: lzota@ufl.edu

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ABSTRACT. *The objectives of this study were to evaluate the effectiveness of different soil moisture thresholds using soil-moisture-sensor (SMS) irrigation control of bell pepper cultivated in plastic mulch. Irrigation treatments were set between 4% and 12% threshold of volumetric-water-content (VWC) which was allotted five irrigation windows/day (of 24 min/event) and bypassed events if the VWC exceeded the established threshold. The control treatment was fixed-time (TIME) irrigation of continuous 2h/day commonly used by producers. Soil water distribution in the soil profile was monitored as well as the nitrate leaching below the root zone using drainage lysimeters. Irrigation treatments set above 10% VWC received 18-41% less irrigation water than the control, however, there was a significant increase in yield compared to TIME. The dynamic of water distribution in the soil profile varied accordingly to the irrigation intensity. Water and NO_3-N captured in lysimeters were lower on SMS-irrigation controlled compared to TIME-based irrigation.*

RESUMEN. *Los objetivos de este trabajo fueron evaluar la efectividad de los sensores de humedad del suelo (SHS) para el control del riego localizado bajo diferentes regímenes de humedad del suelo en un cultivo de pimiento sobre mulching de plástico. Los tratamientos de riego incluyeron el control automático de humedad del suelo entre 4% y 12% de humedad volumétrica programados para dar un máximo de 5 aplicaciones diarias (de 24 min/riego) y saltarse el turno de riego automáticamente si el contenido de humedad del suelo al principio del turno superaba los niveles establecidos. Como control se estableció un sistema por calendario con una aplicación diaria de 2 horas, común en la zona. Los resultados muestran una considerable reducción del volumen del riego (18-41%) cuando controlados por los SHS. La reducción el drenaje y las perdidas por lixiviación del nitrógeno fueron significativamente menores para los tratamientos con SHS comparados con el control.*

INTRODUCTION

Vegetables are a major component of Florida agriculture encompassing about 72,000 ha for production with a crop value of $1.5 billion dollars. Bell pepper is the second most important vegetable produced in Florida in terms of value. With a crop value of 209 million dollars, the average acreage annually planted with bell peppers in Florida is 7,500 ha. Vegetable crops in Florida are irrigated due to the coarse-textured soils with low water holding capacity and soil organic matter content. These soils require frequent irrigation and fertigation to minimize crop stress and to attain maximum production. Irrigation and fertigation practices vary widely among growers but irrigation typically occurs 1-2 times each day in fixed timed events normally with longer events during peak growth stages. Although drip irrigation can be very efficient since water and nutrients are delivered to the crop root zone, mismanagement can lead to over-irrigation and excessive nutrient losses due to leaching. One example of water quality degradation due to nutrient enrichment is the Suwannee River basin where nitrate levels have been increased in recent years. The primary entry path has been shown to be springs which result in mixing of ground and surface water (Ham and Hatzell, 1996; Hornsby and Mattson, 1998). Studies conducted by the Suwannee River Water Management District have reported that groundwater nitrate nitrogen concentrations are elevated along the Suwannee River (Ceryak and Hornsby, 1998). Since irrigation and fertilization are intrinsically linked, appropriate irrigation management is required for these soils in order to avoid nitrate leaching. Despite the N-fertilizer rate recommendation for mineral soils with drip irrigation in Florida of 224 kg N ha^{-1}, growers may opt to apply excessively high N rates to minimize risk of yield reduction due to nitrogen limitations. In addition, on sandy soils, proper irrigation management is decisive to maximize yield, fertilizer and water use efficiency for vegetable crop production. On the other hand, significant reductions in water availability for irrigation use in southeast U.S. have increased the importance of implementation of water conservation practices in agriculture. Agricultural practices such as the use of plastic mulch, drip irrigation and quantitative irrigation scheduling are common in Florida, and they provide growers with a viable option to reduce crop water requirements and thus conserve water resources. Even with these advances, there remains a need for advancement in irrigation management by using real-time monitoring techniques combined with high frequency irrigation application methods based on actual plant water requirements. The use of frequent but low volume irrigation applications via drip irrigation is superior to the more traditional scheduling of few large applications (Locascio, 2005). In the past few years, sensor technology that permits continuous on-farm monitoring of soil water status has become increasingly accessible to commercial producers. Soil moisture sensors (SMS) measure volumetric soil water content (SWC), which can be used to more accurately balance specific crop water requirements. The use of SMS–based irrigation systems can maintain soil water status within upper and lower limits determined by type of soil and crop preventing over irrigation and saving water (Dukes and Scholberg, 2005; Zotarelli et al., 2008; Zotarelli et al., 2009). The objective of this study was therefore to identify suitable irrigation scheduling methods, drip irrigation system design to reduce crop water use and nitrogen leaching while increasing or maintaining pepper yield. We hypothesized that alternative irrigation designs and improved irrigation management will reduce irrigation water requirements and nitrogen leaching of intensively managed pepper production systems.

MATERIALS AND METHODS

A field experiment was carried out at the University of Florida, Plant Science Research and Education Unit, near Citra, FL, during the spring of 2008. The soil has been classified as Candler sand (Buster, 1979). These soils contain 97% sand-sized particles in the upper 1 m of the profile (Carlisle et al., 1988) with a field capacity in the range of 0.10-0.12 (v v^{-1}) in the 0-30 cm depth. The area was rototilled and raised beds were constructed with 1.8 m between bed centers. Granulated fertilizer was incorporated into the beds at a rate of 112 kg ha^{-1} of P_2O_5. Beds were fumigated (80% methyl bromide, 20% chloropicrin by weight) 13 days before transplanting at a rate of 604 kg ha^{-1} after placement of drip tape and plastic mulch in a single pass. Irrigation was applied via drip tape (Turbulent Twin Wall, 0.20 m emitter spacing, 0.25 mm thickness, 0.7 L hr^{-1} at 69 kPa, Chapin Watermatics, NY). Water applied by irrigation and/or fertigation was recorded by positive displacement flowmeters (V100 16 mm diameter bore with pulse output, AMCO Water Metering Systems, Inc., Ocala, FL, USA). Weekly manual meter measurements were manually recorded while data from transducers that signaled a switch closure every 18.9 L were collected continuously by data loggers (HOBO event logger, Onset Computer Corp., Inc., Bourne, MA, USA) connected to each flow meter. Pressure was regulated by inline pressure regulators designed to maintain an average pressure in the field of 69 kPa during irrigation events. The plots were 15 m long, and a tractor mounted hole puncher was used to make 50 mm wide openings at 30 cm intervals in twin staggered rows with each approximately 7 cm from the bed center. A weather station located within 500 m of the experimental site provided precipitation, temperature, relative humidity, solar radiation and wind speed data and this information was used to calculate daily reference evapotranspiration (ET_0) according to FAO-56 (Allen et al., 1998). Crop evapotranspiration (ETc) was based on the product of ET_0 and the crop coefficient (K_c) for a given growth stage (Simonne et al., 2007) and values were reduced by 30% to account for the effect of plastic mulch on crop ET (Amayreh and Al-Abed, 2005) until the plant canopy was 80% full cover of raised bed area. Pepper transplants (*Capsicum annuum* var. "Brigadier") were set on 9 April 2008. Weekly fertigation consisted of injecting dissolved fertilizer salts into fertigation lines. All plots received 247 kg ha^{-1} of K_2O as potassium chloride and 12 kg ha^{-1} of Mg as magnesium sulphate. The experimental design had seven irrigation treatments randomized within four blocks. The N-rate corresponded to 220 kg ha^{-1} of N applied as calcium nitrate (Olson et al., 2005). The irrigation treatments were identified as single drip irrigation (SS) in the center of the bed and double drip (SD) beside plant rows. The irrigation treatments were regulated by the commercial RS500 soil moisture sensor (SMS) controller manufactured by Acclima, Inc. (Meridian, ID). The RS500 unit controls irrigation application by bypassing time clock initiated irrigation events if soil moisture was at or above a preset threshold of volumetric water content (VWC) depending on irrigation treatment (Table 1). The soil moisture sensor probes were installed at a 45 degree angle between two plants that measured the soil moisture in the top 0.15 m of the bed. Timed irrigation windows were specified as five possible events per day, starting at 8:00 am, 10:00 am, 12:00 pm, 2:00 pm, and 4:00 pm for 24 minutes each (2 hr day^{-1} total). Two reference treatments were established, a time-based irrigation treatment with one fixed 2 hr ($TIME_{2h}$, approx. 6 mm day^{-1}) irrigation event per day and fixed 4 irrigation events per day of 24 min ($TIME_{4x24}$, approx. 4.8 mm day^{-1}), both with a single drip line. An overview of irrigation treatments are outlined in Table 1.

Plots were harvested on 62 and 76 days after transplanting (DAT). The harvested area consisted of a central 10.5 m long region within each plot. Pepper fruits were size graded into culls, medium, large, and extra-large. Marketable weight was calculated as total harvested weight minus the weight of culls. Irrigation water use efficiency (IWUE) expressed in kg of fruit per mc^{-3} of irrigation applied was calculated. The volumetric water content of the top soil of the production beds was monitored by coupling time domain reflectometry (TDR) probes (CS-616, Campbell Scientific, Inc. Logan, UT, USA) with a datalogger (CR-10X, Campbell Scientific, Inc., Logan, UT, USA). Soil moisture probes were placed in the beds at two subsequent soil layers which recorded soil moisture values. The upper probe was inserted at an angle in order to capture soil moisture in the top 0.15 m of the profile and the lower probe was inserted vertically below the upper probe recording soil moisture between 0.15 m and 0.30 m. Additional three matrices containing twelve TDR probes each were installed in the SS_{12}, SD_{12} and $TIME_{2h}$ treatments. The matrices were configured in a 4 x 3 formation (vertical x transverse), with horizontal rows buried at 0.07; 0.22; 0.37 and 0.70 m and horizontal rows buried at at 0; 0.15 and 0.30 m from the drip irrigation. The resulting contour maps were created using kriging method provided by Surfer 8 (Golden Software Inc., Golden, CO, USA). Soil electrical conductivity of the soil solution and volumetric water content were measured simultaneously every 15 min by Stevens Hydra Probe II - SD12 (Stevens Water Monitoring Systems, Inc., Portland, OR, USA), with the manufacturer provided factory calibration for sand used in data collection. A sequence of 3 Hydra Probes was installed horizontally in the profile at 0.12; 0.37 and 0.67 m depths and 0.05 m from the irrigation drip line. Drainage lysimeters were installed 0.75 m below the surface of the bed three years prior to the bed formation (Zotarelli et al., 2007). Leachate extraction via a vacuum pumping system occurred weekly, one day before each fertigation event. Total leachate volume was determined gravimetrically, and subsamples collected from each bottle were analyzed for NO_3-N so that total N loading rates could be calculated. Soil solution and soil core extracts were stored at –18 ºC until nitrate and nitrite analysis. Samples were analyzed using an air-segmented automated spectrophotometer (Flow Solution IV, OI Analytical, College Station, TX) coupled with a Cd reduction approach (modified US EPA Method 353.2). Statistical analyses were performed using PROC GLM procedure of (SAS, 2002) to determine treatment effects for yield and IWUE. Means separation testing was performed as needed using Duncan's Multiple Range Test at a confidence level of 95%. For repeated measurements such as plant biomass accumulation volume leachate nitrate leaching, the PROC MIXED procedure of SAS with residual maximum likelihood estimation approach and least squares means of fixed effects were pair-wise compared.

RESULTS AND DISCUSSION

In the first 23 days after transplanting, a plant establishment phase was characterized by the application of approximately 5.5 mm day^{-1} divided in 4 irrigation events, totaling 123 mm applied to each treatment. After the pepper plants were well established, the irrigation treatments were initiated. Each soil moisture sensor controller was programmed to bypass irrigation if the probe read soil moisture at or above the set threshold at the beginning of an irrigation window. During the crop season, programmed irrigation events were skipped which significantly reduced the amount of water applied to soil moisture sensor (SMS) based treatments (Fig. 1). The volume of irrigation increased in order $SS_4 < SD_8 < SS_8 < SS_{12} < SD_{12} < TIME_{4x24} < TIME_{2h}$ (Fig. 1). For the same order, the water savings compared to $TIME_{2h}$ treatments corresponded to 76%; 67%, 65%, 60%; 41% and 24%, respectively. The daily application rates can be translated to 1.5, 2.1, 2.2, 2.6, 3.8 and 4.9 mm d^{-1}, respectively.

The cumulative ET_c for the period after the plant establishment was 170 mm (Fig. 1), which indicates that only treatments SD_{12}, $TIME_{4x24}$ and $TIME_{2h}$ received amount of irrigation water above the cumulative ET_c at end of the season. The soil moisture content as measured by TDR probes had a noticeable increase in soil moisture after each irrigation event throughout the growing season (Fig. A2, B2, C2). Soil moisture sensor based irrigation treatments irrigated for short periods of time which resulted in a relatively small increase in soil moisture, consequently decreasing the volume of percolate. On the other hand, the $TIME_{2h}$ treatment was irrigated for a longer time period which resulted in very pronounced soil moisture fluctuations (Fig. 3 bottom row). These spikes in soil moisture were only temporary, as excess soil moisture that rapidly drained in this sandy soil (Fig. 3 D1).

Table 1. Outline and description of irrigation treatments along with threshold volumetric water content (VWC), total cumulative and daily irrigation application depth.

Treat. codes	Irrigation description	Threshold VWC m^3 m^{-3}	Number of irrigation events Sched.	Irrigated	Skipped	Marketable Yield (Mg ha^{-1})	IWUE kg fruit m^{-3}
SS_4	Acclima Digital TDT RS-500	0.04	266	77	189	26.4 c	32.6 a
SS_8	Acclima Digital TDT RS-500	0.08	266	106	160	30.7 bc	26.0 ab
SS_{12}	Acclima Digital TDT RS-500	0.12	266	117	149	35.4 ab	25.6 ab
SD_8	Acclima Digital TDT RS-500	0.08	266	172	94	30.2 c	27.0 ab
SD_{12}	Acclima Digital TDT RS-500	0.12	266	171	95	42.7 a	20.9 bc
$TIME_{2h}$	No soil moisture sensor, daily fixed time irrigation	-	54	54	0	33.0 bc	9.6 d
$TIME_{4X24}$	No soil moisture sensor, reduced daily fixed time irrigation	-	216	216	0	40.6 ab	15.6 cd

Soil moisture content returned to field capacity within 12 h. The spikes also indicate that the soil water content as measured by the TDR probes rapidly reaches a point above the soil water holding capacity in the soil upper layer, inducing percolation to deeper soil layers, and explaining the higher percolate volume captured in the lysimeters for the $TIME_{2h}$ treatment compared to the other treatments (Fig. 4). In fact, similar spikes in soil water content were observed at below15 cm showing appreciable soil water percolation though the soil profile.

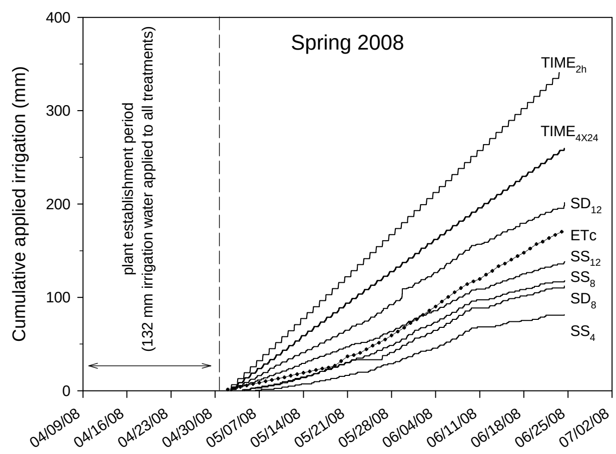

Figure 1. Cumulative irrigation and estimated evapotranspiration (ET_c) after initial plant establishment as affected by different irrigation

scheduling and soil moisture sensor irrigation treatments during spring 2008.

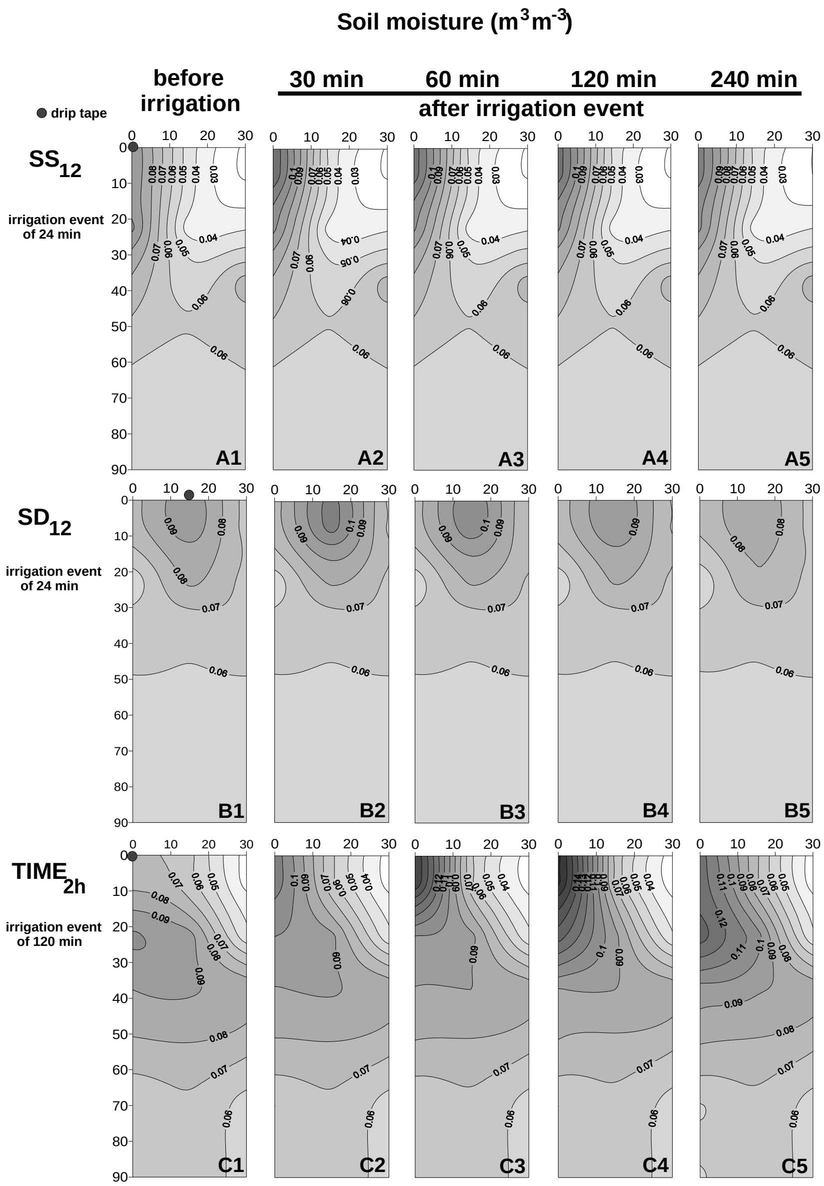

Figure 2. Soil moisture patterns of SS_{12}, SD_{12} and $TIME_{2h}$ treatments at before irrigation, 30, 60, 120 and 240 min after irrigation the beginning of irrigation event. Obs. Irrigation event duration of 24 min for SS_{12} (single center drip) and SD_{12} (double drip) and 2 hours for $TIME_{2h}$.

In terms of soil water availability to plants, the $TIME_{2h}$ treatment initially may provide more favorable growth conditions since the soil remains wetter, thus reducing potential water stress. However, excessive water percolation also may reduce N retention and crop N supply and thereby reduce yield for pepper (Fig. 4). Soil electrical conductivity (EC) was used to assess the effect of irrigation treatments on the movement of the weekly-injected fertilizer solution. Figure 3 shows EC of the upper section of the raised bed for the interval of

48 to 70 days after transplanting (DAT) for SS_4, SS_8, SS_{12} and $TIME_{2h}$ treatments. This monitoring period represented the plant reproductive stage, when the maximum daily N uptake rate was occurring. A narrow relationship between soil moisture and EC was observed for the treatments. The corresponding measurement of EC under $TIME_{2h}$ treatments revealed lower EC values than the SS's treatments. There was a noticeable increase in soil moisture in $TIME_{2h}$ after each irrigation event as measured by the probe placed at the 0.12 and 0.37 m depth (Fig. 3-D1and Fig. 2).

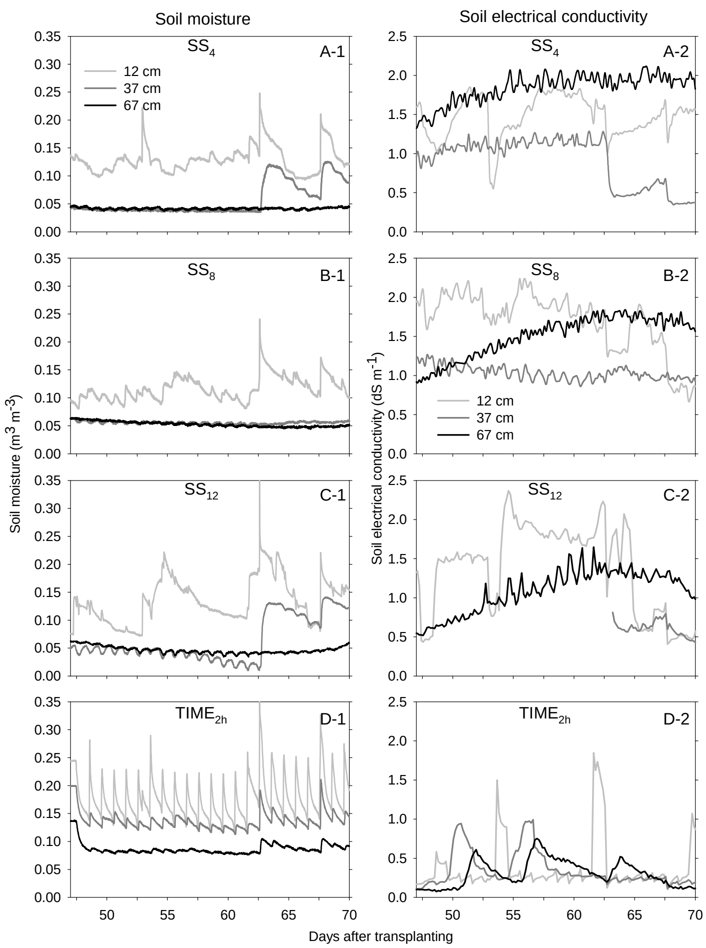

Figure 3. Soil moisture and electrical conductivity of SS_4, SS_8, SS_{12} and $TIME_{2h}$ treatments between 48 and 70 DAT in spring of 2008. Left figures show soil moisture and right figures show soil electrical conductivity at 12, 37 and 70 cm depth.

The SS's treatments were irrigated frequently for short time intervals, which resulted in a relatively small increase in soil moisture, and consequently in minimal vertical displacement and leaching. As a result, for SS's treatments oscillations in soil moisture at 0.37 m were minimal (Fig. 3-A1 to C1), indicating that very little of irrigation water reached this layer. The TIME treatment was irrigated for a longer time period, which resulted in very pronounced soil moisture fluctuations (Fig. 3-D1). These spikes in soil moisture for TIME treatment reached values over 0.20 $m^3\ m^{-3}$, a value well above the soil field capacity, and as a result the excess soil moisture was rapidly drained to deeper soil layers, showing spikes of soil moisture at 0.37 and 0.67 m probes. This clearly demonstrates the mechanistic driving force behind the observed high NO_3-N leaching values for the TIME treatment (Fig. 4) and the pronounced increasing EC in the soil layers below 0.3 m (Fig. 3-D2). As an

example, one day after fertilizer injection (54 DAT), values of EC spiked from 0.2 dS m^{-1} to over 1.5 dS m^{-1} before returning to the initial EC value within the following days at 0.12 m depth. Similar spikes were reported at 0.37 and 0.67 m depth, and both layer showed reduced EC values (< 0.5 dS m^{-1}) after 6 days. By comparison, irrigation management from the SS's treatments produced relatively constant soil moisture and EC values over time, as irrigation water was distributed more evenly across multiple irrigation events according to the soil moisture threshold and thus crop water demand. Therefore, high frequency low volume irrigation methods seems to be much better suited to effectively address the limitation of inherently low water storage capacities of sandy soils. In addition, SS's treatments showed no pronounced spikes in soil moisture and higher values of EC by probes at 0.37 and 0.67 m soil depth, indicating that the volume of water applied at the soil surface did not exceed root water extraction, consequently reducing NO_3-N leaching thus facilitating more efficient water and nutrient use. The only exception was at 61 DAT, when precipitation event of 49 mm occurred. At that moment, an increase in soil moisture was observed at 0.12 and 0.37 m depth for most of the treatments, followed by a decrease in EC for the same depths.
The overall leachate amounts since the transplanting date were 24, 22, 30, 27 and 80 mm, for SS_4, SS_8, SS_{12}, SD_{12} and $TIME_{2h}$, respectively. However, most of the water percolation occurred during the establishment period, except for $TIME_{2h}$, which percolated about 7-8 mm wk^{-1} (Fig. 4 left). Cumulative nitrate leaching at the end of the crop season was significantly higher for $TIME_{2h}$ with 25 kg NO_3 ha^{-1} leached. The measured values for SS_4, SS_8, SS_{12} and SD_{12} ranged from 9 to 13 kg NO_3 ha^{-1} following the same patterns observed for percolated volume (Fig. 3 right).

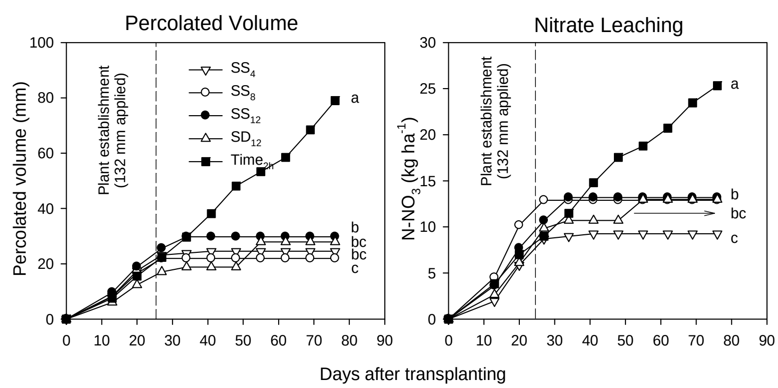

Figure 4. Cumulative leachate volume (left) and cumulative NO_3-N mass leached for different irrigation scheduling and soil moisture sensor irrigation treatments. Treatment means followed by same letter are not different according to Duncan's Multiple Range Test at $P \leq 0.05$.

Irrigation treatments had an important impact on IWUE and pepper yield (Table 1). The marketable yield for green bell pepper ranged between 26.4 to 42.7 Mg ha^{-1}. The use of SMS with 12% VWC threshold and $TIME_{4x24}$ significantly increased marketable pepper yield when compared to the other treatments (Table 1). Pepper yield obtained in these experiments were in the range of those reported in the literature for sandy soils in Florida. The use of soil moisture sensor significantly affected the IWUE (Table 1). The $TIME_{2h}$ treatment had a lowest IWUE values (< 9.6 kg m^{-3}) due to the high irrigation rates applied. It is important to point out that high irrigation rates as applied for $TIME_{2h}$ did not increased yield, conversely, the use of scheduling irrigation by using SMS allowed application of less water, divided in 5 possible irrigation events per day (low volume, high frequency), which resulted in higher IWUE values. While $TIME_{4x24}$ treatment had four irrigation events (high volume, high frequency), which reduced the IWUE, however, there was no negative impact on pepper yields.

CONCLUSIONS

Soil-moisture sensor (SMS) based irrigation systems in pepper significantly reduced the applied irrigation resulting in 41%-60% less irrigation water applied compared to fixed time irrigation ($TIME_{2h}$) without reducing yield. Soil moisture sensor controller thresholds below 8% of volumetric water content significantly reduced the amount of water applied, but also resulted in a significant decrease of marketable yields. The treatment ($TIME_{4x24}$) with four fixed irrigation events a day resulted in similar marketable yields as SD_{12}, SS_{12}, but with lower irrigation water use efficiency. The treatments soil moisture sensors to control irrigation reduced NO_3-N leaching between 40% to 60% compared to the control treatment. The use of double drip improved water distribution across bed, however no additional yield benefit was measured due to the use of double drip comparing SS_{12} and SD_{12} to SS_8 and SD_8

RESULTS AND DISCUSSION

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